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HEAT TRANSFER WITH VERY HIGH FREE-STREAM TURBULENCE*

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ABSTRACT

Stanton numbers as much as 350% above the accepted correlations for flat plate turbulent boundary layer heat transfer have been found in experiments on a low velocity air flow with very high turbulence (up to 50%). These effects are far larger than have been previously reported and the data do not correlate as well in boundary layer coordinates (Stanton number and Reynolds number) as they do in simpler coordinates: h vs. X. The very high relative turbulence levels were achieved by placing the test plate in different positions in the margin of a large diameter free jet. The large increases may be due to organized structures of large scale which are present in the marginal flowfield around a free jet.

FOREWORD

Designing the cooling system for gas turbine blades and vanes requires accurate prediction of the heat transfer coefficient between the blades and the gas stream. For years the heat transfer research community has sought to provide data and models by which these predictions could be made. Academic research has, over the past twenty years, produced an impressive array of data and modeling techniques aimed at this problem. In parallel with the academic effort, industrial researchers and designers have struggled with the realities of heat transfer inside gas turbine engines. Even using the best available theories, large "safety factors" have been needed. The fact is that "unadjusted" predictions based on the best laboratory data and modeling schemes consistently underpredict engine heat transfer, by as much as 50%.

When such a state of affairs has persisted for twenty years, it is likely that something fundamental is being overlooked. Free stream turbulence is a likely candidate. It has been studied, but over this twenty year period opinions have been divided as to whether or not free stream turbulence had any effect on the already-turbulent boundary layer. It has been generally conceded that turbulence alters transition behavior, advancing it to lower Reynolds numbers, but there have been many studies which supported the notion that that was its only effect.

All of the "benchmark" heat transfer data in the literature has been from low turbulence flow fields. Turbulence has been regarded as a 'complicating factor' rather than a natural accompaniment to high energy-density systems. In fact, one of the hallmarks of careful research has been the "quality" of the flow in the tunnel - defined principally by the level of turbulence: the lower the better. Anything over 0.5% was considered a little rude, and one

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had to get below 0.05% before there was any cause for celebration. When turbulence has been studied, it has almost always been "grid-generated" and, in addition, has been allowed to relax until nearly homogeneous and isotropic before its effects on heat transfer have been studied.

Meanwhile, gas turbine engines run with turbulence up to 20-30%, which is probably highly anisotropic and well laced with large coherent structures coming downstream from the combustion chamber. Dils and Follansbee (1977) measured up to 16% in the discharge of a laboratory scale combustor in a bench test. They reported increases in heat transfer of over 50% on the stagnation line of a cylinder in that flow. Recent discussions (Rohde, 1984) suggest 20 to 30% as a reasonable value for the relative turbulence near a typical first turbine nozzle ring.

This paper presents a brief look at the status of a new research program at Stanford, concerning the effects of very high turbulence - up to 50% - on heat transfer through a turbulent boundary layer. The program is following a somewhat unorthodox approach, by usual academic standards. Instead of establishing a well documented flow which contains a specified level of turbulence and studying its effect on heat transfer, the approach has been to find, by experiment, flow fields which are very aggressive in heat transfer and then try to find out what characteristics their turbulence has in common. Over a dozen different high turbulence situations have been tested in preliminary screening experiments, some of which resulted in very high heat transfer. We now seek to carefully document their heat transfer effects, and learn how they produce such high heat transfer rates. The present paper reports on the first of these significantly aggressive flow fields: the flow in the margin of a free jet.

SOME PREVIOUS WORK

Before looking at research laboratory data on heat transfer, it would be well to follow an old industrial dictum and "let the engine vote." Unfortunately, such votes are hard to come by: there is not much available in the open literature about heat transfer measurements on the blades and vanes of a running engine. The next nearest thing is the data available from short duration test facilities using engine components as their test sections. Figure 1 (Dunn, Rae, & Holt, 1983) shows measured distributions of heat transfer coefficient on a turbine stage in a short-duration test facility - the heat transfer coefficient is nearly constant around the entire surface of the blade. There is no evidence of a laminar or transitional region. While this is not "engine data," it is representative of what is believed to frequently occur: high uniform heat transfer around a blade or vane with no discernible laminar region, except perhaps right near the leading edge, and higher values than predicted, overall. Consigny and Richards (1982) show similar data, again from a short duration test facility, in which an increase in turbulence caused a progressive upstream march of the transition event, leaving a high and nearly uniform value of h in the turbulent region.

There have been many studies on the effects of turbulence, going well back in the heat transfer literature. Among these were Kestin (1966), Kearney, Kays, and Moffat (1970), Slanciauskaus and Pedesius (1977), Brown and Burton (1978), Bradshaw and Simonich (1978), Brown and Martin (1979), and Blair (1984).

During the mid-1970's, the consensus was that the principal effect of turbulence was to re-locate the transition event. There were suggestions that strong acceleration made a turbulent boundary layer sensitive to turbulence, based mainly with experience on stagnation regions on bluff bodies. Three examples are cited in some detail because they represent the states of opinion up until the recent work began: Kearney et al (1970), Bradshaw and Simonich (1978), and Blair (1984).

Kearney et al (1970) addressed these two issues: (1) How does the local behavior of an already turbulent boundary layer respond to free stream turbulence, and (2) Does acceleration affect this response? Local effects were separated from those associated with changes in transition behavior by using a different method of data presentation, one based on purely local measures, which did not depend on the location of the virtual origin. A turbulent boundary layer was established on a smooth flat plate in a well-qualified heat transfer test section having three stream-wise parts. The first and third sections provided constant velocity flow, while the second produced a constant K acceleration. Heat transfer Stanton numbers were correlated against the enthalpy thickness Reynolds number, a purely local parameter of the boundary layer. This representation eliminated any sensitivity to the location of transition. Tests were conducted with low turbulence (about 0.7%) and with grid-generated turbulence of 3.9%. The turbulence was generated by a planar grid of round rods, 0.64 cm in diameter set on 2.54 cm centers in a square array.

The results are shown in Figure 2. There is no discernible difference between the high and low turbulence data, either in the flat plate regions or in the accelerated region. The conclusion from this study was that the already-turbulent boundary layer was not sensitive to turbulence of this nature, at this intensity.

Bradshaw and Simonich (1978) reopened the issue when they showed large increases in average heat transfer over a flat plate exposed to grid generated turbulence of up to 7%. A key feature of their experiment was the use of large grid elements of different sizes, aimed at finding the effects of scale and intensity. Figure 3 shows a sample of their results. Although not quantitatively identified, the turbulence caused large effects.

Blair (1984) published a data set which showed, for the first time, that sufficiently high free-stream turbulence could cause turbulent boundary layer behavior to persist down to very low Reynolds numbers. Low enough, in fact, that the data followed the extension of the usual turbulence correlation and intercepted the laminar behavior line. His data are illustrated in Figure 4. In addition, he showed Stanton numbers significantly higher than the low-turbulence correlation: up to 20% higher for 6% turbulence. This difference must be regarded as significant in view of his careful control of experimental uncertainty. Blair's turbulence was again grid-generated, and his papers describe its streamwise evolution through the test section. The intensities ranged from 0.25 to 7%, with length scales from 1.0 cm to 6.5 cm. The average boundary layer thickness was about 4.5 cm. The intensity decreased steadily in the streamwise direction, while the auto-correlation length scale increased. The individual variations were such that their product was nearly constant.

At about this same time, both Schultz, at Oxford, and Dunn, at Calspan, were investigating the effects of transient wake-like disturbances on turbine blade heat transfer (private communications). In both cases, small cylindrical obstructions were passed rapidly across the flow field upstream of a blade model, and time-resolved heat transfer distributions measured. Their preliminary results showed significant increases in heat transfer.

The senior author's early engineering experience with gas turbine combustion chamber development had left him with an acute awareness of the intensities and scales of turbulence in a burner outlet flowfield. It was logical to compare the disturbances produced by Schultz and Dunn to those remembered conditions and to conclude that if a relatively small wake could be so important, then the large scale, high intensity turbulence of a gas turbine combustor ought to have a very profound effect indeed. The present program grew out of these beginnings.

THE BASIS HYPOTHESIS OF THE PRESENT WORK

The basic hypothesis of the present work is that the heat transfer coefficient is a function of both the mean velocity of the flow, and the free-stream turbulence (without, at the moment, defining what is meant by the word turbulence). Treating turbulence as a separate variable leads to planning experiments in which the turbulence can be varied independently from the mean velocity. This viewpoint also leads to a different approach to visualizing the possible outcomes. An operating surface for h can be constructed, based on this hypothesis, using only simple physical arguments. The process is described below.

Let us first consider how surface heat transfer might respond to turbulence in the absence of any mean motion. Consider a closed box full of air, instrumented to reveal the heat transfer coefficient from its inner, bottom surface to the air inside. The mean velocity inside is zero, but there will be some low value of heat transfer coefficient. If now a distributed set of egg-beaters were started into motion, the mean velocity would remain zero but small scale "turbulence" would be developed. It seems reasonable that h would increase as the turbulence increased, slowly at first, then perhaps linearly, and finally slowly again, as it asymptotically approached some ultimate maximum value for very high turbulence.

The "zero-velocity trace" of the effect of turbulence can thus be argued to be an S-shaped curve, having zero slope at very low turbulence and at very high turbulence, and a maximum slope at some intermediate value. We expect that this same general response would be present for non-zero velocities: increasing turbulence would increase h, only slightly at low turbulence intensities but more strongly at high values.

We have ample evidence about how heat transfer behaves with zero free-stream turbulence. The "zero-turbulence trace" is simply the variation of heat transfer coefficient with position along a surface.

Most physical processes vary smoothly as their parameters are changed, and can be represented by "operating surfaces" of low mathematical order. When nothing is known except the two bounding traces, a first estimte of the operating surface can frequently be made by assuming it to be a product function of the two boundary traces.

Figure 5 shows the hypothesized distribution of h along a plate of length L for a turbulent boundary layer for a range of turbulence intensities. For this figure, the free stream velocity is assumed constant. The turbulence values could then be regarded as absolute or relative. At zero turbulence, the heat transfer coefficient shows the typical turbulent boundary layer behavior. As the turbulence gets higher, h rises toward an asymptotic value, which is the same for every position. If this asymptotic state exists, and if the turbulence can be made high enough to approach it, h would be expected to show less and less x-dependence as the turbulence increased. At very high turbulence values, h might become uniform along the surface, dominated entirely by the turbulence.

To this point we have not specified what measure is to be used to characterize turbulence intensity. The usual approach is to use one or more of the Reynolds normal stress terms. It has been suggested, e.g. by Brown and Martin (1979) that turbulence scale and frequency may also be important in this problem. The present results support this notion. There are good physical reasons for believing that both are potentially important, at least at the extremes of very large and very small scales (or very low or very high frequencies). Consider the situation of a hot-wire anemometer wire, where the turbulence scale is large compared with the boundary layer thickness. The fact that we can calibrate these wires in laminar flow and use them to measure turbulence is evidence that the boundary layer is in the same state for all frequencies of disturbances up to 100kHz. Thus, it seems that when the turbulence scale is very large compared to the boundary layer thickness (or frequencies are very low) there is little or no effect. On the other end of the spectrum, it seems unlikely that free stream turbulence would have much effect if the scale of the turbulence was an order of magnitude smaller than the natural scales within the boundary layer. If there is to be a significant effect of turbulence, it most likely will come when the scale of the turbulence is of the same order of size as the boundary layer turbulence (i.e., related to the boundary layer thickness), or a low multiple of it.

To call a flow "turbulent" doesn't say much about it except that it is unsteady in some unpredictable manner (except statistically). One important question which we hope to answer at least partially is: "What aspect of turbulence is responsible for the increase in heat transfer?" There is no a priori assurance that intensity is the appropriate descriptor, nor even intensity combined with length scale. In fact, data from the present program suggests that, even together, these are not sufficient.

Testing this hypothesis requires a flow field with very high turbulence which can be varied at will, and with length scales also variable. The shape of the hypothesized operating surface suggests that low velocity, thick boundary layers will be more strongly affected than high velocity, thin boundary layers. The flow in the margin of a large diameter, low speed, free jet meets these requirements admirably and was the first flow tested. The characteristics of a free jet, and a description of the present free jet facility are contained in the sections below.

THE FREE JET FACILITY

The first flow studied under this program was a free jet, blowing over a flat plate. This was selected because is offers a simple flow field capable of generating very high local turbulence, with significant contributions from large scale, relatively well organized structures. Figure 6 shows the features of a free jet which made it attractive. The mean velocity is well distributed across the jet, from a maximum on the centerline to zero in the surrounding air. The relative turbulence intensity increases dramatically near the outer edge. Relative turbulence intensities of over 50%, based on local mean velocity, can easily be found and the length scales increase almost linearly with distance from the nozzle. With a variable velocity free jet facility, one can find almost any desired combination of turbulence intensity, length scale, and mean velocity.

Figure 7 shows a schematic of the free jet facility. The test plate is shown in a representative position, a few diameters off the axis of the jet and many diameters downstream from the nozzle. For most of the work so far, the test plate has been equipped with side walls, approximately as high as the plate is wide. The plate and its side walls thus form an open channel. Experience has shown that the flow tends to be "frozen" at the conditions existing at the leading edge. The presence of the plate stops entrainment from the bottom and sides. This has the effect of stopping the linear growth of the length scales, and preserving the free stream turbulence properties at those available at the entrance. The plate is shown in two positions: W, aligned with the axis of the jet, and F, aligned with a line through the virtual origin of the jet. When the plate is in the F position, the mean velocity and turbulence quantities are uniform within 1-2% along the plate - a flat plate configuration. When the plate is parallel to the axis of the jet, the W position, the situation resembles a wedge flow - the small positive incidence angle causes the velocity to increase slightly along the run of the plate. The data in the present paper were all taken in the wedge flow configuration. The mean velocity variation along the plate is still small - on the order of 5%.

The test plate is 0.5 m wide and 2.5 m long. The working surface is made of 7 plates of aluminum, each equipped with an electric heater and an array of thermocouples. Side walls on the test plate help "freeze" the flow for the whole length of the plate at the conditions existing at the leading edge of the test plate. Heat transfer is measured by energy balances on the individual segments of the test plate. The free-stream velocity and turbulence are measured with a single hot wire, about 12.5 cm above the surface of the plate, centered over the first test plate. Axial traverses have shown that the velocity increases about 5% when the plate is in the wedge-flow orientation, and about 1% when in the flat plate position. We recognise the inaccuracies of a single hot-wire under such strenuous conditions, but the results are, nevertheless, indicative of the level of turbulence. For the present it is sufficient to have accurate measurements of the increase in heat transfer and a rough measure of the turbulence, those data serve to identify an aggressive flow. Future work will study the structure of the turbulence in detail using one or more probes having orthogonal triple wire arrays, with which we have considerable experience. Turbulence length scales are now being measured using the time-delayed auto correlation of the hot wire signal. In future, the length scales will be determined from the outputs of the triple wire processor.

QUALIFICAITON OF THE APPARATUS

Figure 8 is intended to establish the credibility of data from the present experiments by demonstrating a low-turbulence baseline check and showing evidence of repeatability with high turbulence. For the baseline run, the test plate was installed in low-turbulence, closed loop wind tunnel (HMT-2, in the Thermosciences Division Heat Transfer Lab). A representative set of results are shown as the diamond shaped symbols, lying along the line representing an accepted correlation for turbulent boundary layer heat transfer in a low-turbulence situation. The agreement is within +/- 4%. The conclusion from this series of tests was that the test plate instrumentation was functioning normally, and the results could be believed within the demonstrated accuracy.

The test plate was then removed from the tunnel and set up in the free jet facility. All of the instrumentation remained the same, and the same data interpretation program was used in reducing the free jet data. The leading edge of the plate was 5D downstream of the nozzle exit, and the 2D off the centerline. The surface of the plate was parallel to the axis of the jet. At that location, the mean velocity was 3.6 m/s and the turbulence intensity was 27%. Results are shown from two runs, taken on different days at this same location. No changes or adjustments were made between these two runs. The excellent agreement establishes that the effects reported here are repeatable.

NEW RESULTS

Figure 9 compares typical results from the present program with a set of Blair's (1984) data and with an accepted zero free-stream turbulence boundary layer correlation from Kays and Crawford (1980). The data are plotted in conventional Stanton number versus X-Reynolds number coordinates. The RMS u' value is used as a measure of free stream turbulence. The Stanford cases are at 26% and 48% turbulence, while Blair's data are at 6%. The Stanford data at the highest turbulence show the Stanton number to be almost 350% higher than the baseline results for the same Reynolds number. This case clearly identifies the flow field in the margin of a free jet as an aggressive one as far as heat transfer is concerned. It also seems clear that the data labelled 48% comes from a "more turbulent" flow than the data labelled 26%, but relatively how much more turbulent is unknown. The present data show no sign of laminar behavior and hence no sign of transition. The heat transfer must be considered fully turbulent from the leading edge of the plate. Very high free stream turbulence eliminates the laminar region, as Blair found, but also, for these high values, increases the heat transfer at low Reynolds numbers by as much as three and one half times compared with the accepted turbulent boundary layer correlation.

Figure 10 shows cases from the present program at four different mean velocities with relative turbulence intensity held constant at 25%. The data are plotted as Stanton number versus enthalpy thickness Reynolds number, a purely local parameter - not dependent on the location of the virtual origin of the turbulent boundary layer. These data confirm that the large increases observed in Stanton number are local in nature, which agrees with Blair's conclusion but contradicts Kearney. The spread in the data for the same turbulence intensity shows that fixing the relative turbulence intensity and the enthalpy thickness Reynolds number is not sufficient to assure repeatable results. Neither x-Reynolds number nor enthalpy thickness Reynolds number collects into one correlation the data for different mean velocities. Indeed, this may not be a boundary layer flow at all, in the usual sense of the term.

Comparing the data in Figure 10 to the line representing the established turbulent boundary layer correlation, one sees that high free stream turbulence does alter the streamwise dependence of the heat transfer, as had been anticipated: as turbulence goes up, the slope goes down. In boundary layer problems, the streamwise decay of heat transfer is typically associated with the thickening of the boundary layer. Boundary layer thickness serves as a length scale for the heat transfer problem, and is Reynolds number dependent. If the streamwise dependence of the present data is also associated with the growth of a boundary layer, this boundary layer is not Reynolds number dependent. It may be that the boundary thickness is being set by the turbulence, not by the mean velocity.

Figure 11 is a plot of the same data used in Figure 10, but plotted in terms of the heat transfer coëfficient, h, versus streamwise position along the plate, X. Surprisingly, at any given X, h is the same for all four cases within +/- 4% even though the mean velocities vary by as much as 50%. This figure suggests that, for very high free stream turbulence, the Stanton number should be replaced by a descriptor which does not involve the mean velocity.

CONCLUSIONS

The flow field near the outer margin of a free jet displays very aggressive heat transfer properties. Stanton numbers as much as 350% above the usual turbulent correlations have been observed when the local relative turbulence intensity reaches 50%.

The data are not well correlated by the usual boundary layer parameters, Stanton number and Reynolds number. Data from four runs with the same relative turbulence intensity (25%) but different mean velocities (2.3 to 3.6 m/s) show the same values of h at each x-location (within +/- 4%). Plotting these data in terms of Stanton number and x-Reynolds number introduces considerable separation.

The failure of the usual boundary layer coordinates to collect data from the high turbulence cases into coherent groups suggests that the high turbulence has fundamentally altered the boundary layer state.

ACKNOWLEDGMENTS

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NOMENCLATURE

D	Diameter of jet nozzle
F	Flat plate configuration (Fig. 7)
h	Heat transfer coefficient
K	Acceleration parameter
R	Radial position within the jet
Re(H)	Enthalpy thickness Reynolds number
Re(O)	Momentum thickness Reynolds number
Re(X)	X-Reynolds number
RMS	Root-mean-square
St	Stanton number
TKE	Turbulence kinetic energy
Tu	Turbulence
u'	Fluctuating component of x-directed velocity
U or V	Free stream velocity
U(max)	Velocity at the jet centerline, at X.
W	Wedge flow plate configuration (Fig. 7)
X	Distance downstream from the jet nozzle

REFERENCES

Blair, M. F. (1983), "Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development. Part I: Experimental Data," Journal of Heat Transfer, 105: 33-41, Feb. 1983.

Brown, A., and Burton, R. C. (1978), "The Effects of Free Stream Turbulence Intensity and Velocity Distribution on Heat Transfer to Curved Surfaces," Jn. Eng. for Power, Vol. 100, 1978, pp. 159-168.

Brown, A., and Martin, B. W. (1979), "Factors Influencing Heat Transfer to the Pressure Surfaces of Gas Turbine Blades," International Journal of Heat and Fluid Flow, 1, No. 3, 1979.

Consigny, H., and Richards, B. E., "Short-Duration Measurements of Heat-Transfer Rate to a Gas Turbine Rotor Blade," Jn. Eng. for Power, 104: 542-551, July 1982.

Dils, R. R., and Follansbee, P. S., "Heat Transfer Coefficiency around Cylinders in Crossflow in Combustor Exhaust Gases," Jn. Eng. for Power, Oct. 1977, pp. 497-508.

Dunn, M. G., Rae, W. J., and Holt, J. L., "Measurement and Analysis of Heat-Flux Data in a Turbine State. Part III: Discussion of Results and Comparison with Predictions," 28th Int'l. Gas-Turbine Conference, Phoenix, AZ, March 1983.

Kays, W. M., and Crawford, M. E., Convective Heat and Mass Transfer, McGraw-Hill Book Co., 1980.

Kearney, D. W., Kays, W. M., and Moffat, R. J. (1970), "The Effect of Free Stream Turbulence on Heat Transfer to a Strongly Accelerated Turbulent Boundary Layer," Proceedings of the 1970 Heat Transfer and Fluid Mechanics Institute, edited by T. Sarpkaya (Stanford University Press), pp. 3-14.

Kestin, J. (1966), "The Effect of Free Stream Turbulence on Heat Transfer Rates," Advances in Heat Transfer, pp. 31-32.

Simonich, J. C., and Bradshaw, P. (1978), "Effect of Free-Stream Turbulence on Heat Transfer through a Turbulent Boundary Layer," Journal of Heat Transfer, 100: 671-677, Nov. 1978.

Slanciauskaus, A., and Pedisius, A. (1977), "Effect of Free Stream Turbulence on the Heat Transfer in the Turbulent Boundary Layer," Paper FC(1)-5, Academy of Sciences of the Lithuanian USSR Institute of Physical and Technical Problems of Energetics, Kaunos, USSR.

Wygnanski, I., and Fiedler, H., "Some Measurements in a Self-Preserving Jet," J. Fluid Mech. (1969), vol. 38, part 3, pp. 577-612.

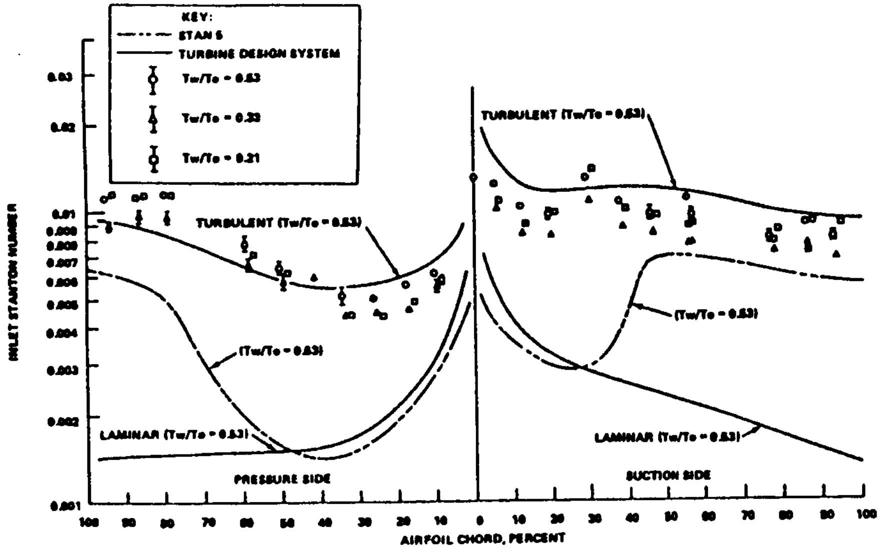

Fig.1 Heat transfer under simulated engine conditions does not always agree with predictions.[Dunn and Rae,1983]

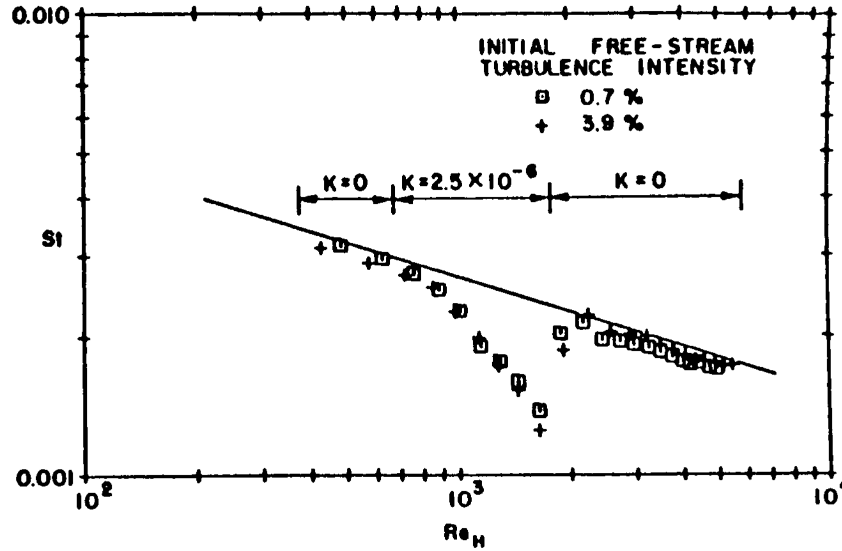

Fig.2 Moderate grid generated turbulence does not effect turbulent heat transfer. [Kearney,Kays and Moffat,1970]

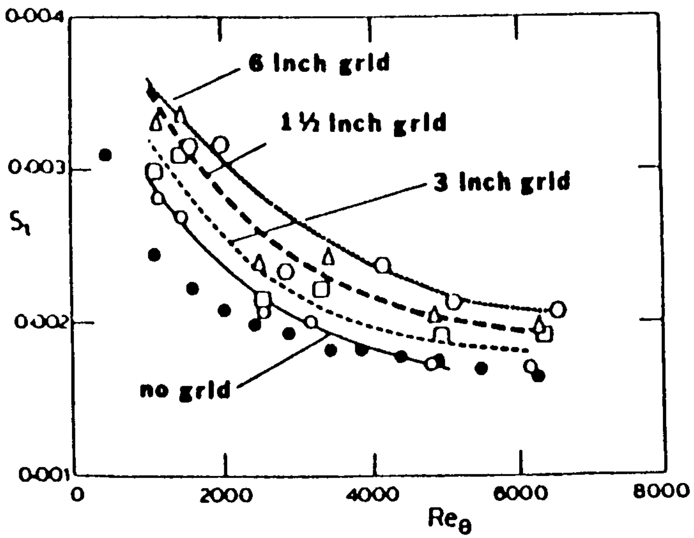

Fig.3 Large scale high intensity grid generated turbulence affects heat transfer.[Simonich and Bradshaw,1978]

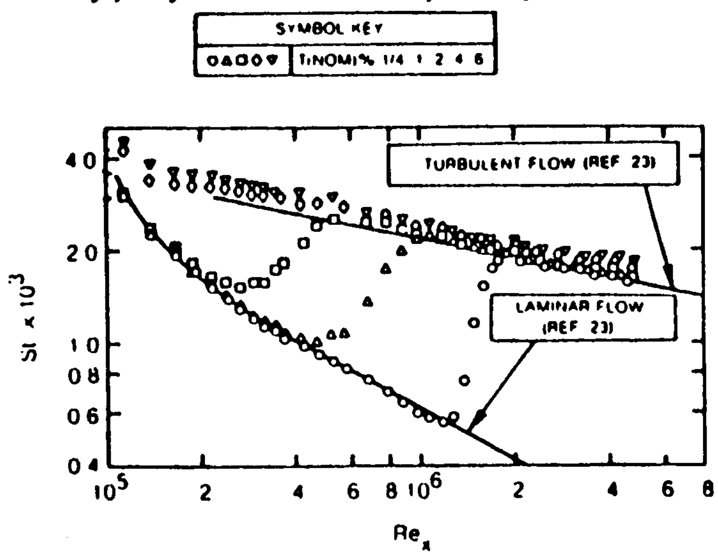

Fig.4 Grid generated turbulence eliminates laminar behavior and raises turbulent heat transfer.[Blair,1983]

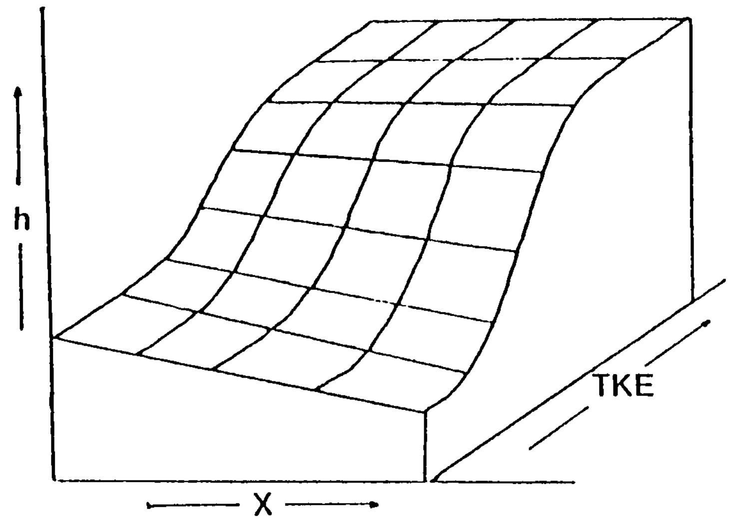

Fig.5 Proposed operating surface for h vs. X and Tu.

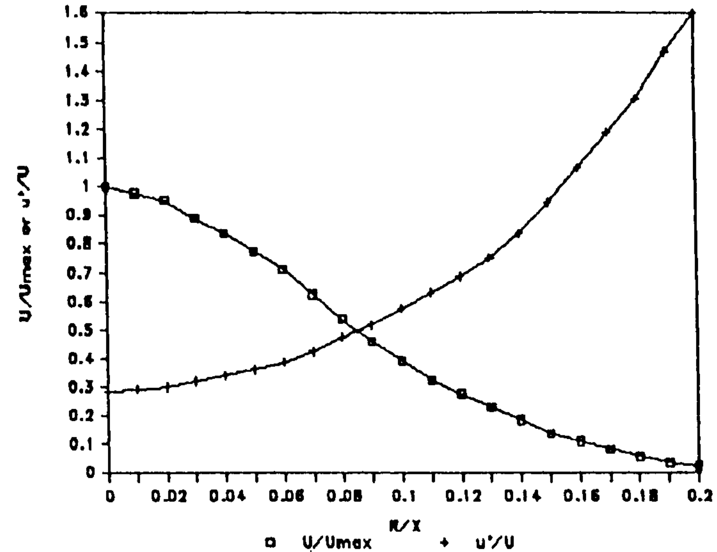

Fig.6 Mean velocity and relative turbulence intensity characteristics of a free jet. [Wygnanski and Fiedler,1969]

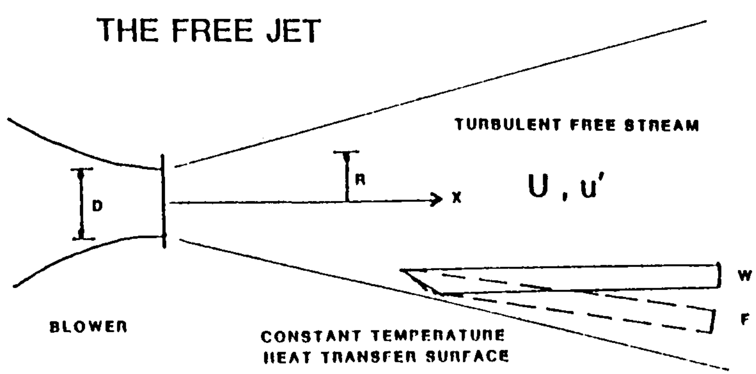

Fig.7 Schematic of the free jet facility.

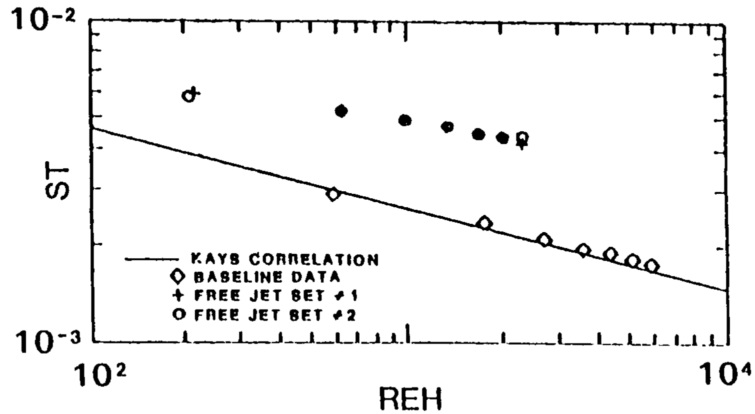

Fig.8 Baseline and repeatability data from the free jet facility.

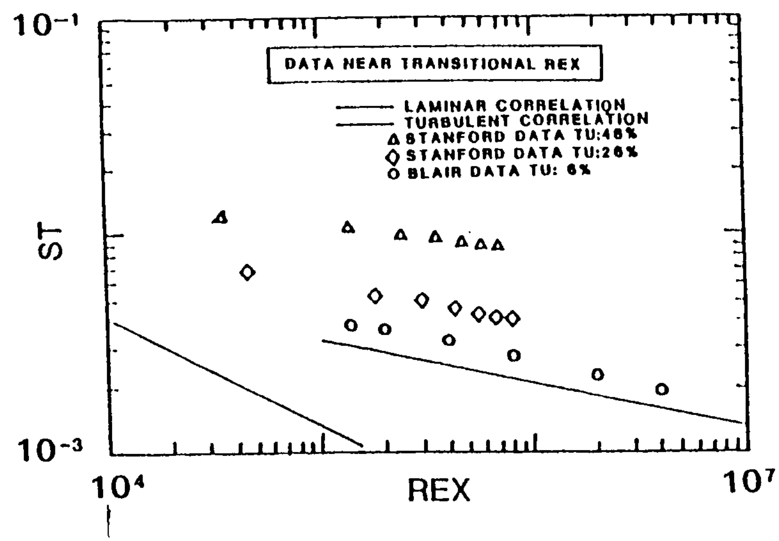

Fig.9 High turbulence causes large effects on St vs. ReX.

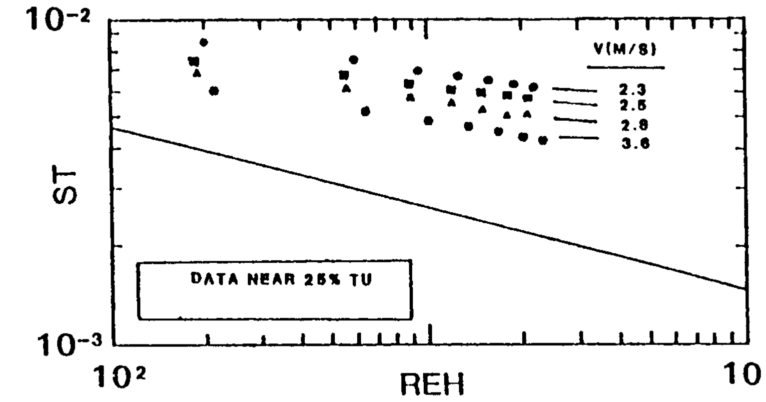

Fig.10 ReH and %Tu are not a sufficient set of descriptors.

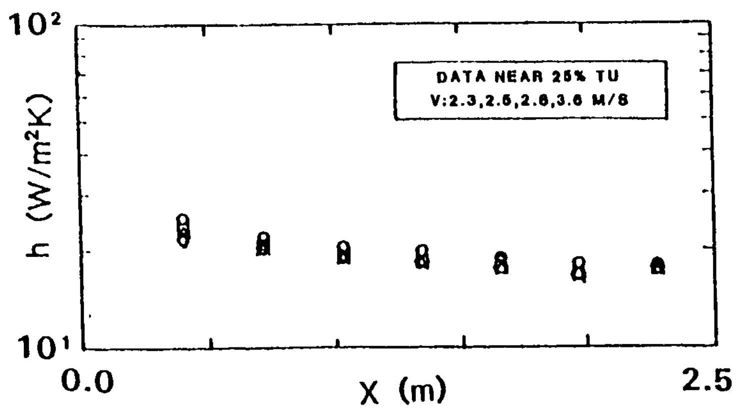

Fig.11 The heat transfer coefficient, h, collects the Fig.10 data better than St.